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ScienceDirect
Physics Procedia 17 (2011) 62–68
Physics Procedia

Physics of Fundamental Symmetries and Interactions - PSI2010

Design of a novel pulsed spin resonator for the beta-decay experiment PERC

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Abstract

The PERC (Proton Electron Radiation Channel) project searches for new physics beyond the Standard Model of particle physics via the beta-decay of free neutrons. This high precision measurement demands perfect knowledge of the key beam parameters, i.e. wavelength distribution, degree of polarisation and time structure. Therefore, we propose a novel design of a spatial magnetic spin resonator, allowing precise velocity selection as well as the accurate definition of the beam's time structure by purely tuning electronic parameters.

Keywords: polarised neutrons, magnetic spin resonator, current-sheet, spin-flipper, beta decay

1. Introduction

The Standard Model of particle physics requires three parameters to describe free neutron decay. These are the element V_{ud} of the CKM quark-mixing matrix, the ratio $\lambda = g_A/g_V$ of axial vector and vector coupling constant as well as the Fermi coupling constant G_F. High precision measurements utilising PERC will make a large number of quantities accessible. The observables are the energy spectrum of the decay neutrons, the parity-violating β-asymmetry A, the proton asymmetry C, the anti-neutrino asymmetry B, the correlation coefficient a, the Fierz interference amplitude b as well as the electron helicity H_e. The over-determination of the problem allows precision checks of the Standard Model and may reveal new physics beyond [1]. For a successful experiment it is crucial to perfectly know the initial neutron beam parameters, i.e. wavelength, pulse width and degree of polarisation. This is achieved by using both a velocity selector and a neutron chopper in the 'standard' setup [2]. The use of a novel pulsed neutron magnetic spin resonator as a replacement for these two components will lead to a higher count rate and will give rise to a unique flexibility in triggering the standard machine parameters by purely electronic means. The technique relies on the fact that upon passage of a polychromatic neutron beam through a spatially alternating transverse magnetic field, as shown in Fig. 1, each neutron in its rest frame creates its individual spin precession frequency, which for given period of the alternating field just depends on the speed of propagation [3, 4]. Then a resonant spin flip takes place if a specific frequency equals the Larmor frequency, determined by the strength of the static guide field. This effect was used by Drabkin et al. [4] to monochromatise a polarised neutron beam. Here we propose a novel design of such a resonator consisting of a sequence of separate modules. It provides high homogeneity of the transversal field oscillations and fulfills the specifications for fast electronic switching which is required for rapid chopping of the beam intensity [5].

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doi:10.1016/j.phpro.2011.06.018

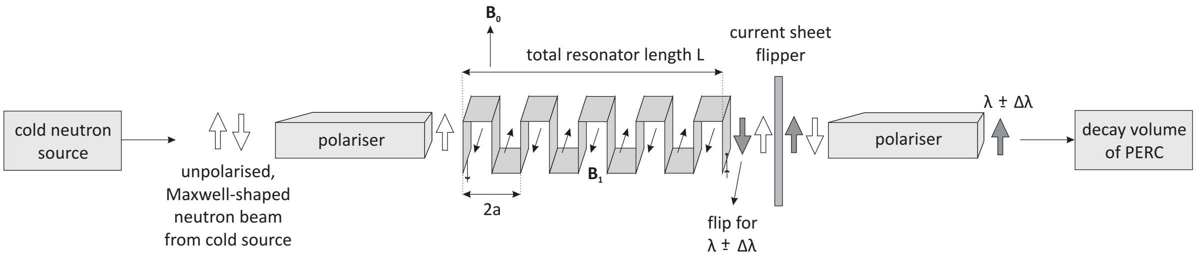

Figure 1: Principle of the beam-tailoring setup at PERC, utilising a modified Drabkin-type magnetic spin resonator with a total length L and a spatial period *2a*. The unpolarised neutron beam coming from the cold neutron source is polarised by means of a supermirror polariser and subsequently enters an alternating transversal magnetic field region. There, each neutron in its rest frame creates its own spin precession frequency according to its individual speed. A subsequent second polariser, in combination with a wavelength-independent current sheet spin flipper, suppresses all neutrons except those which have undergone a resonant spin flip process upon passage through the transversally oscillating field.

Both the selected wavelength and the respective wavelength resolution of this device can be changed almost instantaneously without any mechanical intervention and an arbitrary time structure of the neutron pulses can be realised [6]. Although it was motivated mainly by the requirements of the PERC project, this development could readily find applications in various fundamental precision experiments with cold neutrons. In this article we present appropriate technical solutions for the application of pulsed spatial magnetic spin resonance (PSSR) in the beam tailoring part of the PERC setup.

2. Basic concepts

In 1963 Drabkin proposed spatial spin resonance (SSR) as a method to achieve velocity-selective spin flipping of a polarised neutron beam [4]. At the original Drabkin-type spin resonator a DC current flowing through a zigzag folded Aluminum foil produces a spatially alternating transversal static magnetic field $\mathbf{B}_1$. In the passing neutrons' rest frame, each neutron experiences a time-dependent field with an oscillation frequency

$$\omega(\upsilon) = \frac{\pi\upsilon}{a} \quad \rightarrow \quad \omega(\lambda) = \frac{\pi h}{ma\lambda}\,. \tag{1}$$

There h is Planck‘s constant, m the mass of the neutron, υ its velocity, and a the spatial half period of the transversal resonator field. Placing the resonator in a homogeneous vertical magnetic guide field $\mathbf{B}_0$, a full spin flip will take place for neutrons propagating with the ‘resonance wavelength’

$$\lambda_0 = \frac{\pi h}{|\gamma|\,ma} \cdot \frac{1}{B_0}\,, \tag{2}$$

where $\omega(\lambda_0)$ equals the Larmor frequency $\omega_0 = |\gamma|\,B_0$, if the amplitude condition

$$\frac{B_1}{B_0}\frac{L}{a} = (2k+1)\,\frac{\pi}{2} \qquad (k = 0, 1, 2, ...) \tag{3}$$

is fulfilled. $\gamma = -1.833 \cdot 10^8\,\mathrm{s}^{-1}\,\mathrm{T}^{-1}$ denotes the neutron gyromagnetic ratio and L the total length of the resonator. The number of resonator periods N defines the wavelength resolution of the flipped neutrons to be

$$\frac{\Delta\lambda}{\lambda} \cong \frac{0.8}{N}. \tag{4}$$

The probability for neutrons with a certain wavelength to perform a full spin flip is given by a $(\sin(x)/x)^2$-shaped function. Due to the odd higher harmonics in the Fourier spectrum of the transversal magnetic field, additional resonance maxima occur also at odd multiples of the resonance wavelength. It was demonstrated experimentally that even the most simple straight resonator configuration can serve as an electronically tuneable energy analyser in

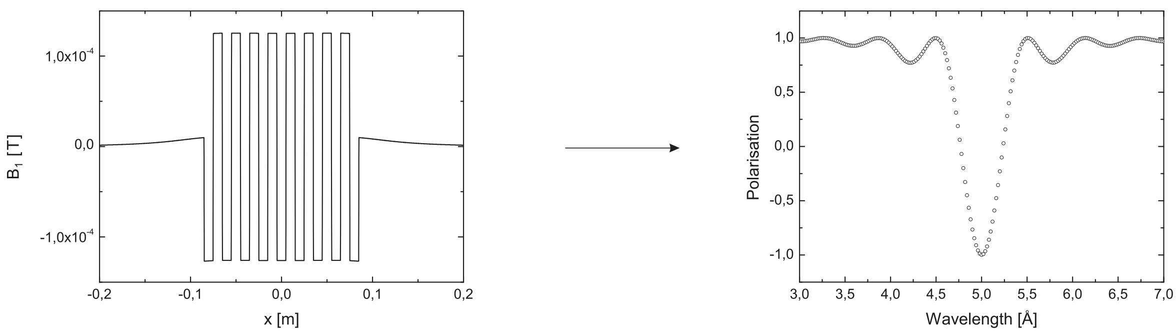

Figure 2: (*Left*) Here, the alternating transversal field B_1 of a resonator with total length $L = 17$ cm and a spatial half period $a = 1$ cm was calculated. To get a full spin flip at a desired wavelength of 5 Å, a stationary guide field of 1.357 mT and an absolute value of $B_1 = 0.125$ mT is needed. (*Right*) The simulation of a neutron beam passing through such a resonator yields a $(\sin(x)/x)^2$-shaped curve.

an inverted geometry neutron time-of-flight spectrometer [7]. In a similar setup, a Drabkin-type resonator was used for time-of-flight focusing of neutrons of different wavelengths without any mechanical intervention [8]. For the implementation within the PERC project, a modified resonator will be used not only as monochromator but also as a beam chopper. Therefore this resonator consists of a sequence of separate, individually switchable resonator stages. Then a so-called 'travelling wave' mode of operation becomes possible, which leads to a complete decoupling of the wavelength resolution of the resonator from its time resolution [5, 6].

3. Calculations and Simulations

The considerations of the following resonator setup to be used both as monochromator and chopper device are governed by the specific requirements of PERC: i.e. a central wavelength of $\lambda \simeq 5$ Å with $\Delta\lambda/\lambda \leq 0.1$, a high degree of polarisation, and a precisely defined time structure. Therefore a resonator configuration consisting of 96 stages was chosen (half period $a = 1$ cm), defining the best achievable wavelength resolution as $\Delta\lambda/\lambda \simeq 1.7 \times 10^{-2}$. If four stages are switched in the same direction, meaning an effective reduction to 24 half periods, the wavelength resolution will reduce to about 6.7×10^{-2}. Six coupled stages lead to a wavelength resolution $\Delta\lambda/\lambda \sim 0.1$, as requested typically by PERC. As shown in Fig. 2, a rectangularly shaped alternating transversal field will lead to disturbing subsidiary maxima in the polarisation of the flipped beam. However, for the travelling wave-type resonator, consisting of individually switchable elements, it is easy to modulate the field according to a *Gaussian* shape and thus to get rid of the side peaks. The transversal component of the magnetic field shaped by 96 individual stages as well as the polarisation of the neutron beam after its passage through such a configuration are shown in Fig. 3, where an evenly distributed wavelength spectrum was assumed.

For the spectrum of the cold neutron source used for the PERC project the suppression of the first order harmonic will be essential. As Agamalyan *et al.* [3] have shown, sinusoidal oscillations of the alternating field $\mathbf{B_1}$ are necessary to eliminate all higher order maxima. In practice, one possibility to realise sine-shaped field oscillations is to approximate them by using a resonator configuration consisting of a set of several layered meander foils. Fig. 4 shows simulation results both for a resonator consisting of single current sheets as well as for an approximation of the sine-function by means of eight layers for each sheet. Whereas the second order harmonic is totally suppressed, the first order harmonic is still visible, but clearly reduced in intensity.

3.1. Degree of polarisation

Since the achievable precision of PERC crucially depends on the degree of polarisation and the knowledge of this quantity, an arrangement of two crossed supermirrors will be used as polariser and analyser, respectively, each reaching an extremely high degree of polarisation $P = 0.997$ [9]. However, any polarisation deviating from exactly 100% inevitably will produce background intensity. To estimate this background, let us assume that an unpolarised

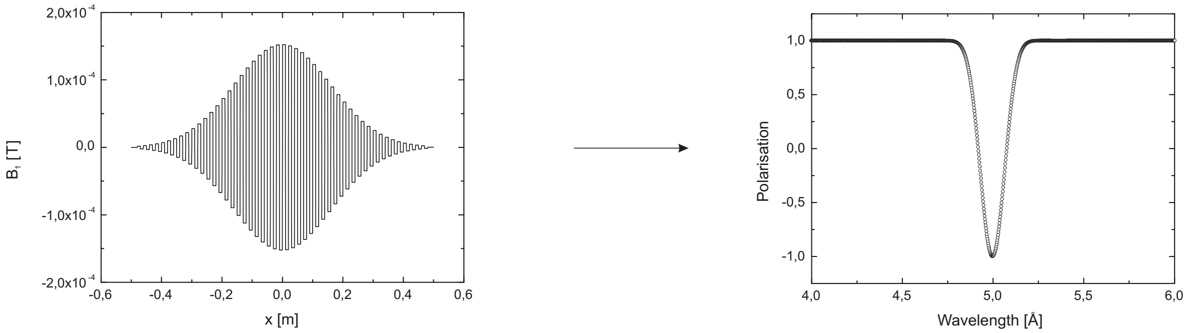

Figure 3: *Gaussian*-shaped modulation of the transverse field-component eliminates the subsidiary maxima of the spinflip probability. The simulation was performed for a resonator configuration with $L = 96$ cm, $a = 1$ cm. The mean value of B_1 was set to a value yielding full spin inversion for a resonance wavelength of 5 Å.

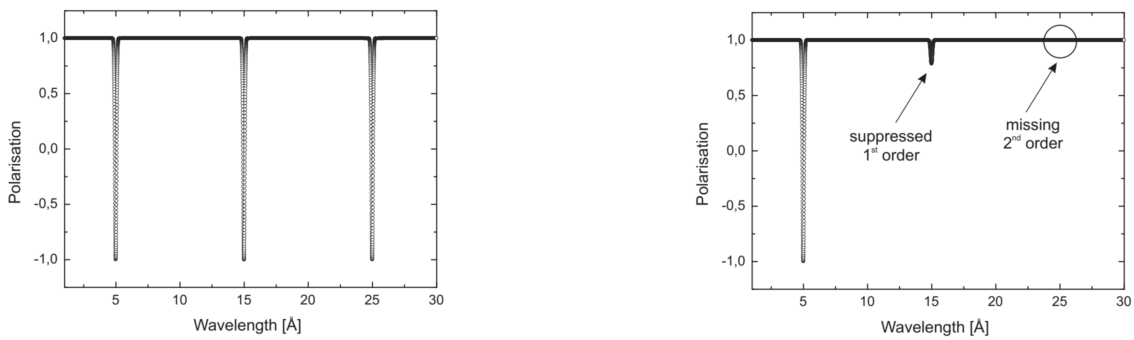

Figure 4: Due to the odd harmonics in the Fourier spectrum of the transversal magnetic field, full spin flip maxima also occur at odd multiples of the resonance wavelength (*left*). Current sheets composed of 8 layers are used to approximate sine-shaped field oscillations. This is sufficient to eliminate the second order harmonic and to largely suppress the first order harmonic (*right*).

beam of $N_0(\lambda)$ neutrons from the cold source is arriving at the polariser of the arrangement shown in Fig. 1. If both the spin resonator and the current-sheet flipper are not in operation (*transmission state*, TS), an amount of

$$N_{\uparrow}^{\mathrm{TS}}(\lambda) = \frac{N_0(\lambda)}{2} T_{\mathrm{P}} T_{\mathrm{SR}} T_{\mathrm{A}} \tag{5}$$

spin-up neutrons will pass the setup. The transmission factors of the respective components, i.e. polariser, spin resonator and analyser, are given by T_{P}, T_{SR} and T_{A}. However, also a small number of spin-down neutrons

$$N_{\downarrow}^{\mathrm{TS}}(\lambda) = \frac{N_0(\lambda)}{2} T_{\mathrm{P}} \frac{1 - P_{\mathrm{P}}}{1 + P_{\mathrm{P}}} T_{\mathrm{SR}} T_A \frac{1 - P'_{\mathrm{A}}}{1 + P'_{\mathrm{A}}}, \tag{6}$$

will reach the detector, where P_{P} denotes the effective polarising power of the first pair of crossed supermirrors[2]. The notation P'_{A} formally takes into account that the probability of a spin-down neutron of an unpolarised beam to pass the analyser is not necessarily exactly identical to that of a spin-down neutron, which has already been preselected by its passage through the polariser.

[2] For reasons of simplicity we do not explicitly take into account the (small) wavelength dependence of the transmission factors and the polarising powers of polariser and analyser, which will be calibrated by time-of-flight measurements.

In the so-called *dark state* (DS) only the current-sheet flipper is activated, which inverts the spin orientation of all neutrons with 100% efficiency irrespective of their wavelength[3]. In this case the detected intensity of spin-up neutrons follows as

$$N_{\uparrow}^{\mathrm{DS}}(\lambda) = \frac{N_0(\lambda)}{2}\, T_{\mathrm{P}} T_{\mathrm{SR}} T_{\mathrm{A}}\, \frac{1-P_{\mathrm{A}}}{1+P_{\mathrm{A}}}\,, \tag{7}$$

whereas the corresponding number of spin-down neutrons is given by

$$N_{\downarrow}^{\mathrm{DS}}(\lambda) = \frac{N_0(\lambda)}{2}\, T_{\mathrm{P}}\, \frac{1-P_{\mathrm{P}}}{1+P_{\mathrm{P}}}\, T_{\mathrm{SR}} T_{\mathrm{A}}\ . \tag{8}$$

To examine the *open state* (OS) not only the current-sheet but also the spin resonator is turned on, whose wavelength-dependent spinflip probability shall be denoted by $P_{\mathrm{SF}}(\lambda)$. For neutrons which had left the polariser in a spin-up state one obtains in front of the analyser the intensities

$$N_{\uparrow\uparrow}(\lambda) = \frac{N_0(\lambda)}{2} T_{\mathrm{P}}\, T_{\mathrm{SR}} P_{\mathrm{SF}}(\lambda) \tag{9}$$

$$N_{\uparrow\downarrow}(\lambda) = \frac{N_0(\lambda)}{2}\, T_{\mathrm{P}}\, T_{\mathrm{SR}}\ (1-P_{\mathrm{SF}}(\lambda)) \tag{10}$$

and likewise for those with spin-down state

$$N_{\downarrow\uparrow}(\lambda) = \frac{N_0(\lambda)}{2}\, T_{\mathrm{P}}\, \frac{1-P_{\mathrm{P}}}{1+P_{\mathrm{P}}}\, T_{SR}\, P_{\mathrm{SF}}(\lambda) \tag{11}$$

$$N_{\downarrow\downarrow}(\lambda) = \frac{N_0(\lambda)}{2}\, T_{\mathrm{P}}\, \frac{1-P_{\mathrm{P}}}{1+P_{\mathrm{P}}}\, T_{SR}\ (1-P_{\mathrm{SF}}(\lambda))\ . \tag{12}$$

The intensities behind the analyser are then delivered by summing up these terms and considering the transmission and the analysing power of the second supermirror arrangement:

$$N_{\uparrow}^{OS}(\lambda) = N_0(\lambda)\, T_P T_{SR} T_A \frac{1}{1+P_P} P_{\mathrm{SF}}(\lambda) \tag{13}$$

$$N_{\downarrow}^{OS}(\lambda) = N_0(\lambda)\, T_P T_{SR} T_A \frac{1}{1+P_P}\, \frac{1-P'_A}{1+P'_A}\, (1-P_{\mathrm{SF}}(\lambda))\ . \tag{14}$$

In Fig. 5 the relative intensities of spin-up and spin-down neutrons passing the entire setup are plotted as a function of the neutron wavelength: the open state is shown as small red circles, the transmission state and the dark state as horizontal black lines. As seen from the right part of this figure, in the dark state a fraction 1.5×10^{-3} of neutrons (compared to the spin-up intensity given by Eq. (5)) with unwanted spin-down state passes through the resonator setup including two pairs of crossed supermirrors (each providing a very high polarisation power $P = 0.997$). In the open state this small fraction is further reduced by up to two orders of magnitude in the selected wavelength band, but remains unaffected in all other spectral regions. However, since the PERC version proposed here exploits a pulsed mode of operation (the travelling wave mode) of the magnetic monochromator, it will be possible to properly gate the detectors so that the contribution of the spectral regions outside the chosen wavelength band to the measured intensity are kept as small as possible. In PERC pulsed mode the position of the decaying neutrons out of this band is sharply defined by their time-of-flight. This information is preserved for the charged decay products by their arrival time at the detector and determination of their energies. Within the chosen wavelength band the relative background intensity will be of the order of 10^{-5} (assuming a flipping ratio of the order 10^2), and hence be negligible. This spin-down contribution is a result of the slightly imperfect polarisation by the mirrors, defining the non-zero transmission state level for the spin-down neutrons. In addition, for the 'standard' setup of PERC, a continuous mode is included as described in [2]. In this case the resonator itself would be operating continuously in non-travelling wave mode so that the additional suppression of neutrons with wrong spin orientation in the chosen wavelength band is not effective and the total background intensity transmitted during the open state of the spin resonator cannot be avoided. Therefore, a polarisation very close to $P = 1$ is essential for high precision measurements and the use of additional ^{3}He spin filters is envisaged for PERC.

[3]We tacitly assume that both the current-sheet flipper and the resonator do not cause any depolarisation of the beam. In practice this can be almost perfectly guaranteed by careful technical design, in particular by avoiding field inhomogeneities across the beam diameter.

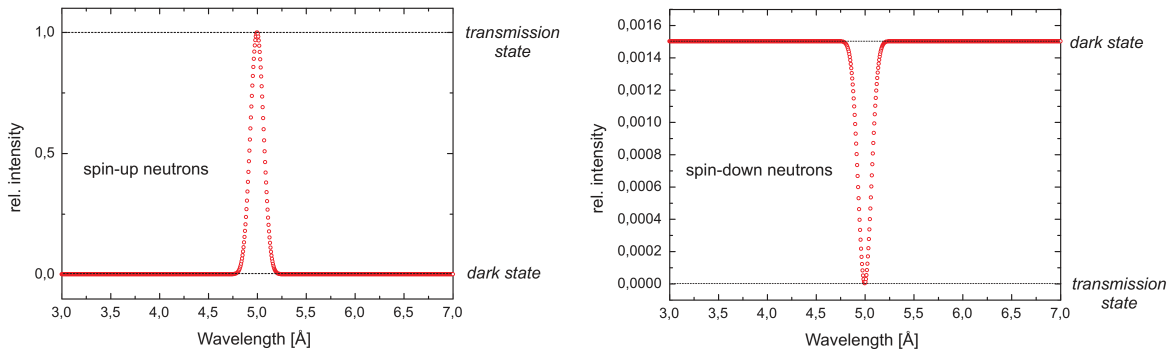

Figure 5: Resulting relative intensities of spin-up and spin-down neutrons after passing the resonator setup including the wavelength-independent current-sheet spin flipper with 100% efficiency and two pairs of crossed supermirrors, each with a polarising power $P = 0.997$.

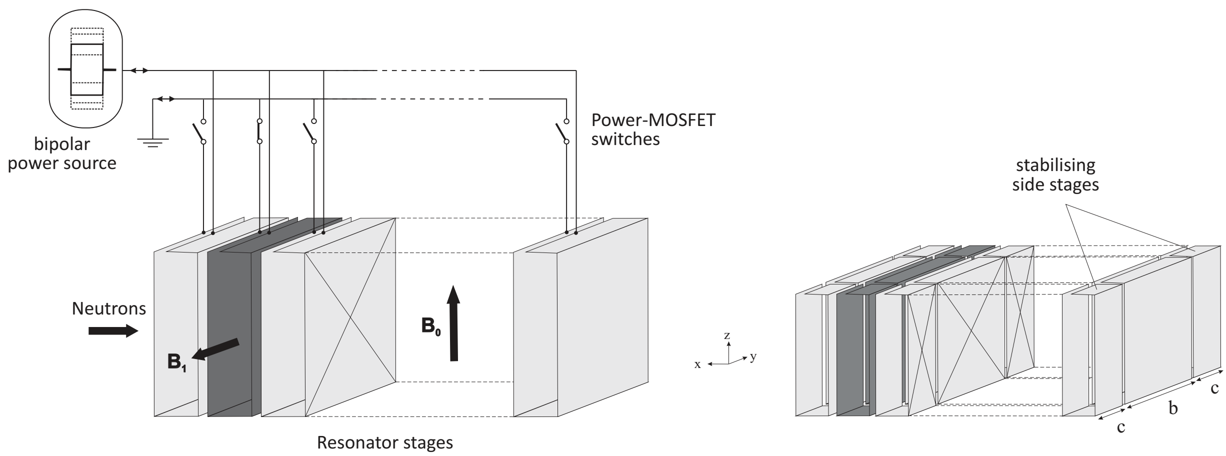

Figure 6: Resonator design with a total number of 96 main resonator stages, individually operated by Power-MOSFET switches and high-current power supplies (left). Our calculations suggest that a width of $b = 8$ cm and a height of 12 cm is sufficient for the main stage. In addition, we envisage the use of stabilising side stages of the same height and smaller width of about $c = 3$ cm to homogenise the transversal field component in y-direction (right).

3.2. Technical Realisation

As described in the previous section, a proper travelling wave mode of operation of the resonator requires specific modulations of the alternating field. Therefore, we designed the device with 96 individual switchable Aluminium resonator stages. Thus, a maximum of flexibility in performing shaping-techniques can be realised. On one hand a discrete approximation of a Gaussian becomes possible which removes all side maxima. Furthermore, it is possible to significantly suppress higher order maxima by operating several stages with the magnetic field pointing in the same direction, thereby approximating a sine-function. In addition, it is planned for the final setup to use stabilising side stages to homogenise the magnetic field in transversal direction (Fig. 6). At present we consider a neutron beam cross section of $6{\times}6\,\text{cm}^2$ for the PERC instrument. According to our field calculations resonator stages of 8 cm width and 12 cm height will provide for a sufficiently homogeneous magnetic field across the neutron beam. The homogeneity of the field is even more improved by adding side stages of $c \geq 3$ cm width to the setup, as indicated in Fig. 6. The specific shape of these resonator stages is a consequence of the required homogeneity of the magnetic field within each section and the very low inductance of each stage as a crucial pre-condition for fast electronic chopping. A more detailed justification of the finally chosen resonator configuration, including simulations of the magnetic field homogeneity of different arrangements, can be found in [6]. The resonator's quality in fast electronic chopping depends on a low value of the half period a, which defines the shortest possible pulse duration $\Delta t_{\min} = a/\upsilon_0$. We plan to use stages with $a = 1\,\mathrm{cm}$ leading to a minimally achievable pulse duration $\Delta t_{\min} = 12.6\,\mu\mathrm{s}$ for neutrons with a velocity $\upsilon_0 = 791\,\mathrm{m/s}$ ($\lambda_0 = 5\,\text{Å}$). The width of the transmitted wavelength band can be varied via the electronically controllable effective resonator length. Due to the travelling wave mode of operation it will be completely decoupled from the time structure of the neutron pulses, starting with a sharpest value $\Delta\lambda/\lambda \simeq 1.7 \times 10^{-2}$ in the case of separately activating all 96 resonator stages.

4. Discussion & Outlook

As we have shown, a travelling wave mode Drabkin-type magnetic spin resonator can be used simultaneously both as velocity selector and as fast electronic chopper for polarised cold neutron beams. Simulations showed that a suppression of unwanted side maxima in the polarisation can be achieved easily by a *Gaussian*-shaped transversal field. Moreover, higher order maxima, occurring at odd multiples of the resonance velocity, can be reduced by approximating a *sine*-function instead of a rectangular field profile, by using several resonator layers or stages. Solely the degree of polarisation of the polarising system will define the switching ratio of the resonator and the amount of background passing through into the decay volume of PERC. Nevertheless, neutrons passing through during the dark state can be used to gather additional statistics, thereby improving the precision of the resulting data and allowing for a better estimate of systematic errors. The benefit of the pulsed magnetic spin resonator will be an increased count rate as it allows to replace both the velocity selector and the chopper from the 'standard' setup. Although designed specifically to meet the requirements of PERC, such a flexible device in general could find applications in neutron scattering setups or various neutron optical experiments with cold neutrons.

Acknowledgements

Financial support by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung (Project No. I528-N20, MONOPOL) and by the FP7 Grant Agreement No.226507-NMI3 (Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy) is gratefully acknowledged.

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